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Agricultural Memorandum No. 937

Weather and Spray Drift Part III: maximum likely rates of uptake of volatilised chemicals on downwind surfaces

by N Thompson

1. Introduction An earlier Memorandum (Thompson, 1981) included a calculation of the probable concentrations of vapour at the surface at different distances downwind from a sprayed area from which the vapour was volatilising at a known rate. Table 1 shows these concentrations for sprayed fields of different sizes producing uniform area sources of vapour: the fields are assumed to be sufficiently broad for the effects of crosswind diffusion of vapour to be negligible. The letters A, B and D refer

Table 1. Surface vapour concentrations downwind from fields of different along-wind lengths emitting 1 unit of vapour per square metre per sec (mean speed of downwind travel ($\bar{u}$) = 2 ms^{-1})

Downwind distance from field edge (m)	Concentrations (units m^{-3})								
	Field length=100m			200m			500m		
	A	B	D	A	B	D	A	B	D
5	9.1	14.1	22.6	11.3	18.0	30.7	14.5	23.4	40.7
10	7.3	11.6	19.0	9.4	15.3	26.9	12.6	20.7	36.8
20	5.6	9.0	15.3	7.5	12.5	22.8	10.6	17.7	32.4
50	3.5	5.8	10.5	5.2	8.9	16.2	8.1	13.7	26.0
100	2.3	4.0	7.3	3.9	6.5	12.0	6.2	10.7	20.9
200	1.4	2.5	4.7	2.5	4.3	8.2	4.5	8.2	15.7
500	0.7	1.2	2.4	1.2	2.3	4.5	2.5	4.7	9.6
1000	0.4	0.7	1.4	0.7	1.3	2.7	1.5	2.9	6.3

to Pasquill stability categories (respectively very unstable, moderately unstable and neutral). Concentrations for other wind speeds but the same stability category may be obtained by multiplying tabulated values by $2/\bar{u}$. The remainder of this Memorandum will consider the derivation of factors by which these concentrations may be multiplied in order to determine the maximum rate of uptake by a plant-covered surface.

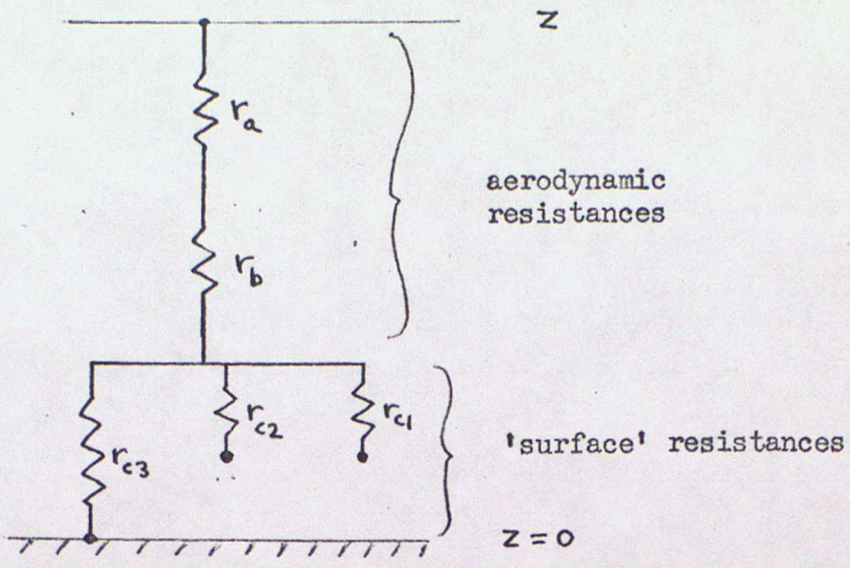

Figure 1 Resistance network for vapour uptake by a plant-covered surface

2. Vapour uptake by surfaces

2.1 General considerations It is convenient to develop the necessary theory by using a resistance analogue of the transfer process (Fowler and Unsworth, 1979), which is shown in Figure 1. r_a is the usual aerodynamic resistance to transfer of momentum to the surface and r_b is the additional resistance for mass (vapour) transfer (for which bluff - body transfer i.e. transfer by pressure forces, is not possible). r_{c1}, r_{c2} are bulk surface resistances acting in parallel and refer respectively to stomatal and cuticular pathways. r_{c3}, which is also in parallel, accounts for transfer to the soil surface. It is the sum of contributions controlling transfer at the actual soil surface and transfer within the crop canopy between soil surface and a bulk reference height in the canopy: this reference height is typically around $0.7h$, where h is the height of the canopy.

The aerodynamic resistance r_a will be a function of the roughness length of the surface, wind speed, atmospheric stability and reference height z (Thompson 1978). Its value in near-neutral conditions with z_o =0.01 and the reference height z 2m above the zero plane displacement height of the surface is

$$(r_a)_N = \frac{6.25}{u(z)} \left(\ln(2/0.01)\right)^2 \qquad (1)$$

$$= 88 \text{ sm}^{-1} \text{ for } u(z) = 2 \text{ ms}^{-1}$$

:values in very unstable conditions would be about 60% of this. The corresponding neutral value for a 5 ms^{-1} wind speed is 35 sm^{-1}, and about 20% smaller in the very unstable case.

Chamberlain (1974) suggested that

$$r_b = (B u_*)^{-1} \qquad (2)$$

where u_* is the friction velocity and B^{-1} is a function of the Schmidt number Sc : thus he recommended the relation $B^{-1} \propto (Sc)^{0.8}$ where $Sc = \nu / D_v$ with ν the kinematic viscosity and D_v the vapour diffusion coefficient. He suggested a typical value of B^{-1} for water vapour transfer of around 5. The diffusion coefficient is usually inversely proportional to the square root of the molecular weight M_v, and so for other vapours

$$B^{-1} \simeq 5 \left(\frac{D_{\text{WATER VAPOUR}}}{D_v} \right)^{0.8} = 5 \left(\left(\frac{M_v}{18} \right)^{\frac{1}{2}} \right)^{0.8} \qquad (3)$$

so that

$$r_b \simeq \frac{1.6}{u_*} M_v^{0.4} \qquad (4)$$

Spray chemicals usually have much larger molecular weights than common atmospheric vapours such as water vapour or carbon dioxide. If a typical value of M_v for the chemical is around 300 then for the wind speed of $2\ ms^{-1}$ and roughness length of 0.01 m, r_b has a value of about $100\ sm^{-1}$. At $5\ ms^{-1}$ r_b would be around $40\ sm^{-1}$.

Values for r_a and r_b may be used in conjunction with appropriate values of r_{c1}, r_{c2} and r_{c3} to determine the rate of uptake of chemical F by the surface, through the expression

$$F = (C(z) - C(o)) \left(r_a + r_b + \left(\frac{1}{r_{c1}} + \frac{1}{r_{c2}} + \frac{1}{r_{c3}} \right)^{-1} \right)^{-1} \qquad (\text{units } m^{-2} s^{-1}) \quad (5)$$

where $C(z)$ is the vapour concentration at reference height z, and $C(o)$ is the effective concentration at the surface.

2.2 Uptake through stomata only If the canopy is very dense, and there is negligible cuticular uptake, then a maximum rate of uptake via stomata may be obtained by assuming that the surfaces within the substomatal cavities are perfect sinks for the vapour. In this case $r_{c2}, r_{c3} \gg r_{c1}$ and $C(o)$ =0 so that equation (5) reduces to

$$F = \frac{C(z)}{r_a + r_b + r_{c1}} \qquad (6)$$

: rate of uptake of vapour is unlikely to be large and so the variation of vapour concentration with height will be small; thus the exact height at which z is measured will not be critical - a value of 2m will be satisfactory for the present purpose.

A typical bulk stomatal resistance for water vapour transfer from a dense canopy with open stomata is around 40 sm^{-1}. The corresponding value for the chemical vapour would then probably be 40 $(M_v/18)^{\frac{1}{2}}$, or around 160 sm^{-1} for vapour with a molecular weight of 300. Then, with the wind speed of 2 ms^{-1} it follows from eq (6) that $F \simeq C(z)/350$.

The rate of uptake is often expressed in terms of a "deposition velocity", v_g which is defined through

$$F = v_g C(z) \qquad (7)$$

In the present case then v_g has a value of around 3×10^{-3} ms^{-1}.

Sensitivity of deposit to molecular weight is relatively small: increasing M_v to 600 decreases the deposit by only about 25%. Sensitivity to wind speed is difficult to judge. Doubling the speed roughly halves r_a and r_b in near-neutral conditions (but has a smaller effect on r_a in more unstable conditions). However, for a rate of production of vapour from the sprayed area independent of wind speed, $C(z)$ is inversely proportional to speed but production of vapour may itself be influenced by wind speeds. The point will not be discussed further because a consideration of the factors affecting the rate of volatilisation of vapour from the target area is outside the scope of this memorandum.

2.3 Uptake through cuticle only. Here the maximum deposit is obtained by assuming the cuticle is a perfect sink so that $r_{c2} = 0$. Equation (6) then becomes

$$F = \frac{C(z)}{r_a + r_b} \qquad (7)$$

leading to a deposition velocity of around 5×10^{-3} ms^{-1} for a vapour with a molecular weight of 300, so uptake is nearly twice as rapid as through the stomatal pathway.

2.4 Uptake when the canopy is sparse Here a significant part of the transfer of vapour may be to soil rather than plant. If the canopy is very sparse then the flux of vapour to the plants may be obtained using the relation

$$F(\text{per unit plant area}) = \frac{C(z) - C(o)}{r'_{c1,c2} + r'} \qquad (8)$$

where $C(o)$ is the concentration at the plants' sink, $r'_{c1,c2}$ are the average stomatal or cuticular resistances per unit leaf area, and r' is the boundary layer resistance of the plant material, again per unit leaf area. A rough value for the last is (following Monteith, 1973)

$$r' = \frac{1}{u(p)} (Re)^{1/2} \left(\frac{\nu}{D_v}\right)^{2/3} \qquad (9)$$

where $u(p)$ is the average wind speed through the plant, R_e the Reynolds number, and $\nu \simeq 1.5 \times 10^{-5}$ m^{2}s^{-1}. A minimum value for r' is obtained by assuming that $u(p)$ refers to the wind speed at mid-height of the plant leaf area, with the speed measured away from the plants. The roughness length of a well-cultivated surface which is sparsely planted with a crop with foliage mid-height of say 0.1 m is probably around 0.01 m, so that $u(p)$ is about 0.9 ms^{-1} for a 2 m wind speed of 2 ms^{-1}. Taking $M_v = 300$ leads to a value for D_v of around 0.6×10^{-5} m^{2}s^{-1}. Thus, for a leaf of average width ℓ,

$$r' \simeq \frac{1}{0.9}\left(\frac{0.9 \times \ell}{1.5 \times 10^{-5}}\right)^{1/2}\left(\frac{1.5}{0.6}\right)^{2/3}$$

$$\simeq 500\,\ell^{1/2}$$

$$\simeq 90 \text{ sm}^{-1} \text{ for } \ell \simeq 0.03 \text{ m}$$

r_{c1} or r_{c2} will be a few times larger than their bulk values for a full crop cover, so maximum fluxes per unit plant area, (assuming perfect sinks for the vapour), via cuticular or stomatal pathways will be respectively $\sim C(z)/90$ and $\sim C(z)/800$ for the chosen wind speed and surface roughness.

3. Discussion The results obtained in § 2.2 and § 2.3 when used with Table 1 suggest that the uptake of vapour by plant-covered surfaces at distances a few hundred metres downwind from extensive vapour sources could exceed 1% of the source strength. Thus, for a case where 10% of the chemical deposited on the target area subsequently volatilises, the uptake might exceed 0.1% of the target deposit. However this conclusion must be treated cautiously because it assumes that the appropriate receiving surfaces of the plant are perfect sinks for the vapour, and remain so throughout the period of uptake. In practise the assumption of perfect sinks may never be true, or may only be true for initial uptake of vapour, after which concentrations of the chemical absorbed at the receiving surface may increase to large enough values to slow down or prevent further uptake.

Any comments or suggestions on this paper should be referred to the author.

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